

## MODELING OF SEA SPRAY DROPLETS IN THE OCEAN

by

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*Droplets are known to play an important role in momentum, heat, and moisture transfer between the ocean and atmosphere. A lot of scholars and experts aim to investigate the effects of droplets on the climate and make precise forecast for hurricane conditions. So the profiles of droplets concentration at different heights above the sea surface are important. For a better study of the momentum and energy transport among the boundary layer, we also need to know the distribution of droplets with different radii. After wave break, with the coupled effects of inertia, gravity, wind updraught, and turbulent mixing, droplets can be transported to certain heights above the sea surface. In the present study, we develop a modified subgrid-scale flow field model coupled with the large eddy simulation to investigate the profiles of spray droplets concentration after wave break. The results in our simulation show that, the distribution of the droplets with the same radii in vertical direction is roughly Gaussian distribution, and the maximum appears at the height nearly above the significant wave height. For different radii, the concentration of droplets with larger radii can be higher than that of the smaller ones at some heights. Since the droplets in our model only include the spray droplets generated by wave break, the data will not be identical with the measurement in the open ocean and laboratory, which include all the kinds of droplets above the ocean.*

*Key words: sea spray, vertical distribution, large eddy simulation, spume droplets*

### Introduction

Droplets play an important role in the fields of optical and meteorological sciences. Whether and how the droplets can influence the heat [1] and moisture transfer have been investigated by a lot of scholars and experts, who have described and tried to quantify both the bubble and spume production mechanism [2]. Droplets are primarily produced by two processes—wave break and bubble burst. According to the different mechanism of the generation, droplet can be divided into three types, namely spume droplets, film droplets, and jet droplets [3].

Under the action of wind, there form waves on the ocean surface. Waves break at the crest, spume droplets and bubbles are generated. Bubbles burst at the sea surface, film droplets and jet droplets are produced and eject into the air [4]. Droplets derive from breaking waves are always larger than the droplets created by the bubbles. Spume droplets are much larger than bubble-generated droplets and are launched with principally horizontal trajectory with an initial upward angle roughly equal to the wave slope [5].

Once created, droplets are carried up and down by turbulence [6]. Under the comprehensive action of wind, gravity, inertia, and turbulent mix, the activity area of droplets can

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be at some heights above the sea surface, so droplets may have a significant effect on the latent and sensible heat transfer between the atmosphere and the ocean [7, 8]. The flux of momentum and heat must be related to the number of droplets with different radii, or the volume flux of droplets [9].

Leeuw *et al.* [10] have measured the droplets from 10-100  $\mu\text{m}$  by using a Rotorod inertial impactor in North Atlantic in 1983, and depict the droplets distribution in vertical direction. It is the first time who measures the vertical profiles of droplets in the open ocean. The results show that above some given heights (roughly the significant wave height), the average concentration decreases with height, and the concentration of droplets decreases with radii when the radii are between 10  $\mu\text{m}$  and 100  $\mu\text{m}$ . He speculates that, upward air motion induced by wind can balance the gravitational forces and carry the aerosol from the production zone to some higher altitudes.

Andreas *et al.* [11] have done a lot of work to investigate the droplets and their effects to the air-sea heat and moisture. He was especially concerned with the droplets with radii between 10 and 300  $\mu\text{m}$  make the biggest contributions to the heat fluxes. In another report by Andreas *et al.*, [6] the mean wind speed at significant wave amplitude and the ejection velocity of jet droplets with radii between 20 and 300  $\mu\text{m}$  agree best with the implied effective production velocity. When the wind speed comes to 9 m/s or higher, spume droplets tend to dominate the flow field and make the most contribution to the heat and moisture transfer, and the initial radii are almost no smaller than 20  $\mu\text{m}$  [12, 13]. At high wind speed like the storm condition, spray heat flux has been conjectured to be the most important among all the heat transfer between the atmosphere and the ocean [14]. So here, for the accuracy of our simulation, we choose the radii of droplets between 20 and 250  $\mu\text{m}$ .

Two laboratory experiments have been made by Fairall *et al.* [5] in the Water Research Laboratory called SPANDEX I and SPANDEX II at the years of 2003 and 2010. These experiments tried to estimate the source function which includes the effects of wind speed, wave breaking and surface from ambient droplet concentration measurements and sought to relate the spray mass flux to an effective wind-forced flux of surface energy fluctuations associated with active breaking crest regions. In his review, the droplets produced by spume are not influenced by only one fundamental parameter or there is no clear consensus on the fundamental parameters. The results show that radii about 100  $\mu\text{m}$  and smaller dominate the profile of the droplets. From the theory of the measurement we can learn that all of the three kinds of droplets including spume droplets, film droplets and jet droplets are in the raw counts of the statistics. So the smaller droplets may be not only produced by the waves break, but also by the bubbles burst.

Large eddy simulation have been used by Sullivan *et al.* [15] for the surface gravity wave effects in the oceanic boundary layer and Liang *et al.* [16, 17] had successfully simulated the evolution of bubbles and dissolved gases in the ocean by means of large eddy simulation (LES) coupled with a multi-size multi-gas bubble model, their model includes the effects of advection, diffusion, and bubble buoyant rising. Because the LES has a theory of "filter", Followed Kolmogorov microscale theory, the turbulence can be separated into different size scales, so we speculate that LES can also be used for droplets.

In this paper, we aim to develop a large eddy simulation model coupled with a modified subgrid-scale (SGS) model to simulate the experiment done by Fairall *et al.* in 2003. Our models incorporate the effect of the subgrid-scale eddy viscosity. The coupled model and the related droplet source parameterizations and scaling arguments are briefly described and the influence of different parameters is described.

### Model description

Followed Fairall *et al.* [18], the aerosol particle conservation equation for the number concentration  $n$  of droplets with radius  $r$  can be described as:

$$\frac{Dn}{Dt} = -\frac{\partial F_z}{\partial z} \quad (1)$$

where  $Dn/Dt$  is the material derivative of the droplets concentration, and  $F_z$  – the flux variable of droplets of radius  $r$  at the height of  $z$ :

$$F_z = \overline{w'n'} - D_p \frac{\partial n}{\partial z} - V_g n + \overline{w'_s n'} + S_n \quad (2)$$

The first terms on the right hand side represent turbulent transport, the second term on the right hand side is the molecular diffusion, the third term is the mean fall speed, and the fourth term on the right hand side is slip term due to the inertia of the droplets, and the last term is the source function at height  $z$  for droplets of radius  $r$ .

$S_n$  can be related to the number of droplets of radius  $r$  increment created per unit volume per second at a specified height  $Q_n$ , and can be written as:

$$S_n(z) = \int_z^\infty Q_n(z) dz \quad (3)$$

Here we have to introduce another parameter  $A_{1/3}$ , which is called the significant wave amplitude, the mean distance above mean sea level of highest one third of the waves [11]. Followed Wilson [19], the significant wave amplitude can be computed as:

$$A_{1/3} = 0.015U_{10}^2 \quad (4)$$

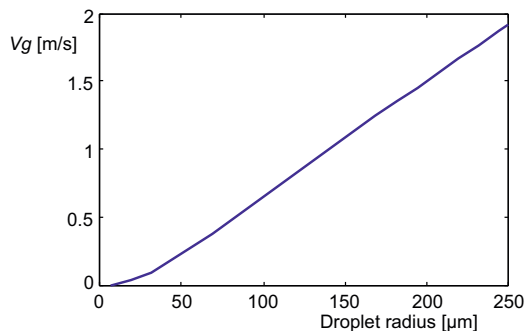
Here  $U_{10}$  is the wind speed of 10 meter above the ocean surface, but since the model of our simulation is based on the laboratory facility,  $u^* = 1.6$  m/s, and  $h = 0.11$  m, the concrete parameters in our simulation can be find in the model of the experiment done by Fairall *et al.* [5]. See the details of the experiment; you can find them in the paper reported by Fairall *et al.*

### Results and discussions

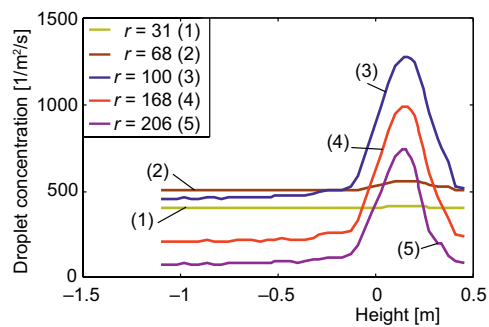
From eq. (2), we can know that before getting the distribution of the droplets in the vertical direction, it is necessary to confirm the mean gravitational settling velocity of the droplets. Following the work of Fairall *et al.* [18], fig. 1 shows the function relation between radii and the gravity settling velocity.

After the wave break, the droplets generated by the breaking waves forced by the combined actions of gravity force, inertia, and the wind stress, coupled with the convection and turbulence mixing. With the increasing radii of the droplets, the effect of the gravity force seems to dominate and the droplets tend to fall back to the water. When the radii of the particles are so small that their gravity cannot offset the updraught caused by the wind stress [10], the particles suspended in the atmosphere and become the aerosols.

The vertical profiles we get from the numerical experiments showed in fig. 2 have the same features compared to the measurements done by Leeuw [10]. The maxima are ob-

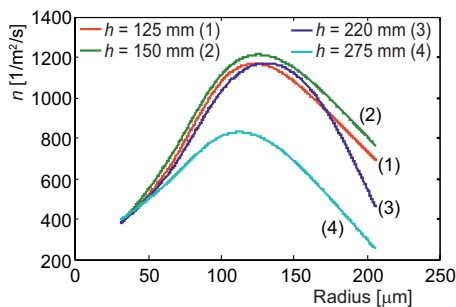


**Figure 1.** The variation of the mean gravitational settling velocity with the increase radii of droplets

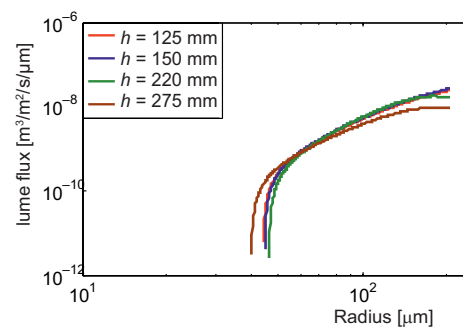


**Figure 2.** The number of spume droplets at different height above the sea surface with the increase of radii from 30  $\mu\text{m}$  to 250  $\mu\text{m}$

served approximately at the reference height, above the reference height, the concentration decrease with height. But in our experiment, the results are that, at the height above the sea surface, or some heights, the concentrations of the droplets with larger radii are higher since in Leeuw's measurements, the concentration of droplets decrease with radii. Here we conjecture that droplets generated by bubble bursting are not included in our numerical experiments, we just simulate the droplets generated by the wave break [20]. So, since most of the droplets with smaller radii are generated by bubble bursting or the effects the evaporation makes the large droplets diminish, the scale of droplets in the open ocean and the laboratory can be less than the theory analysis.



**Figure 3.** The variation of droplets with the increase of radii at the given heights above the surface



**Figure 4.** The spray volume flux size spectra at the give heights showed in fig. 3

From figs. 3 and 4, we can see that, the concentration of droplets at the height of 15 cm is larger than others, even than the significant wave height. Spume droplets was first created nearly at the breaking wave crest by the wind force tearing off the wave crest and roughly follow the slope of the wave [5], after that, droplets are carried up and down by turbulence because of their mass, spray droplets cannot follow the turbulence exactly [6]. However, at the time of one second after the wave break, the mixed force can drive to the different heights.

The profile of the droplets in vertical direction is roughly obeys Gaussian distribution. But in the layer where  $z > h$ , we can see that the slope of the curve is sharp and the num-

ber of the droplets is less. We conjecture that in the region above the reference height, the effect of the gravity prevents the droplets from propagating to the higher region, and the energy transfer from the wave break is restricted, so the inertia cannot drive them too far.

For larger droplets, the effects of gravity are much more significant compared to the effect of inertia and friction. So the number of the droplets with larger radii in the breaking region is much larger than that of the droplets in other regions. As  $z$  increases, the concentration of larger droplets decreases faster with height.

### Conclusions

We couple a modified subgrid-scale flow field with a large eddy simulation model for the spray droplets. The spray droplets are generated by the injecting of the energy transfer from wind to wave and break. With the impact of the flow field, the droplets produced by wave breaking can be sufficiently mixed under the action of the turbulence. The coupled model is used to study the distribution of spray droplets created by wave breaking. After wave break, droplets can be transferred to some given heights above the sea surface with the impacts of gravity, wind updraught, inertia and turbulent mix. And the existence of droplets can influence the heat transfer between the ocean and atmosphere.

Droplets are first created nearly at the wave crest, and forced by the action of turbulent mixed, gravity and wind updraught, they can be transferred to some certain heights above the ocean surface. Andreas [2] demonstrate, however, that spume droplets are probably more important than bubble-derived droplets in transferring heat and moisture across the air-sea interface because of the number and volume produced and the rapidity with which spume droplets exchange heat and moisture with the air.

The profile of the droplets in vertical direction is roughly normal distribution. The max appears at the height nearly above the significant wave height, and the droplets with small radii created by wave break are not always more than others at all heights. Droplets measured in the open ocean and laboratory must include all the three kinds of droplets. Since the experiment in laboratory may have the measurement artifact, and the droplets produced by bubble bursting are not considered in our model, the data in our numerical experiment cannot be all the same as the data Fairall *et al.* got. But when it comes to the works of Andreas *et al.*, we can find the resemblance.

For a further step, if we can relate our model with the model designed by Liang *et al.*, [16, 17] which include not only the effects of wave break, but also the Stokes drift and Langmuir circulations and near-surface TKE dissipation, we can get the profile of all the droplets above the sea ocean and make an accurate numeral model of droplets. With the concentration of droplets, we can investigate the heat and moisture transfer between the ocean and atmosphere.

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